A Client/Server System for Remote Diagnosis of Cardiac Arrhythmias

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Health care practitioners are often faced with the task of interpreting complex heart rhythms from electrocardiograms (ECGs) produced by 12-lead ECG machines, ambulatory (Holter) monitoring systems, and intensive-care unit monitors. Usually, the practitioner caring for the patient does not have specialized training in cardiology or in ECG interpretation; and commercial programs that interpret 12-lead ECGs have been well-documented in the medical literature to perform poorly at analyzing cardiac rhythm. We believe that a system capable of providing comprehensive ECG interpretation as well as access to online consultations will be beneficial to the health care system. We hypothesized that we could develop a client-server based telemedicine system capable of providing access to (1) an on-line knowledge-based system for remote diagnosis of cardiac arrhythmias and (2) an on-line cardiologist for real-time interactive consultation using readily available resources on the Internet. Furthermore, we hypothesized that Macintosh and Microsoft Windows-based personal computers running an X server could function as the delivery platform for the developed system. Although we were successful in developing such a system that will run efficiently on a UNIX-based workstation, current personal computer X server software are not capable of running the system efficiently.

Keywords: telemedicine, knowledge-based systems, model-based diagnosis, cardiac arrhythmias, Internet

INTRODUCTION

Computer-assisted interpretation of the ECG has been very helpful in the real-time monitoring setting, having been shown to be far more sensitive than humans in screening for ventricular tachycardia and ventricular fibrillation [1, 2, 3]. However, the real-time monitors are designed to ignore P waves in an attempt to reduce false alarms due to artifactual signals. Thus, none of the real-time monitors can distinguish confusing rhythms such as the harmless Mobitz I (Wenckebach) versus dangerous Mobitz II second degree atrioventricular block. Further, no available commercial ECG interpretation system attempts to distinguish the origin of wide-complex tachycardia (relatively harmless supraventricular versus potentially lethal ventricular), despite the availability in the literature of heuristics for doing so [4], or to distinguish frequent premature ventricular complexes from the harmless parasystole. In addition, they do not attempt to distinguish atrial fibrillation conducted rapidly down an accessory pathway from ventricular tachycardia, even though the treatment for one is very different from the treatment for the other.

These distinctions are difficult for nonspecialist medical personnel to make and are frequent causes for Cardiology consultation in community and major referral hospitals that have in-house Cardiology services. The clinical importance of complex cardiac rhythms is accentuated in rural primary care facilities without health care providers with special training in the interpretation of complex rhythms. The options available to health care providers in those settings are familiar to any physician or nurse without such training who has worked in the middle of the night in any facility without a 24-hour in-house attending internist or cardiologist. Those options are (1) treat the rhythm as malignant until proven otherwise by the subsequent clinical course, and accept the costs and side effects of the treatment; (2) treat the rhythm as benign, hope for the best, and accept the potential morbidity or mortality of not rendering correct treatment; (3) wake up the consultant internist or cardiologist and ask him or her to come to the hospital to review the ECG (or receive it at home by fax if that capability is available); or (4) transport the patient to the nearest hospital with in-house arrhythmia expertise. The last two options carry their own costs to the consultant and to the patient, respectively.

To assist these practitioners in managing patients with complex cardiac rhythms, we are developing a telemedicine system for remote diagnosis of cardiac arrhythmias and on-line real-time cardiac consultations. We hypothesized that (1) such a system could be developed using resources readily-available on the Internet and (2) that Macintosh and Microsoft Windows-based personal computers running an X server could function as the delivery platform for the system. The system that we are developing provides health care providers access to the capabilities of a knowledge-based cardiac arrhythmia interpretation system under development in our laboratory and access to an on-line cardiologist for real-time interactive consultation. The system is being developed using the client-server paradigm [5] and will utilize the networking protocols utilized on the Internet for communication, namely TCP/IP.

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METHODS

An ECG interpretation and on-line cardiac consultation telemedicine system must contain the following components:

1. an "expert" ECG interpretation component capable of explaining its reasoning using hypermedia-based documents,
2. a data annotation and manipulation component,
3. an output display component,
4. a hypermedia display system,
5. an online consultation system capable allowing interactive image manipulation and text-based conversation simultaneously, and
6. the necessary servers to manage the data flow.

The capabilities of each of these components and the Internet resources from which each derived are presented. A schematic representation of the system is shown in Figure 1.

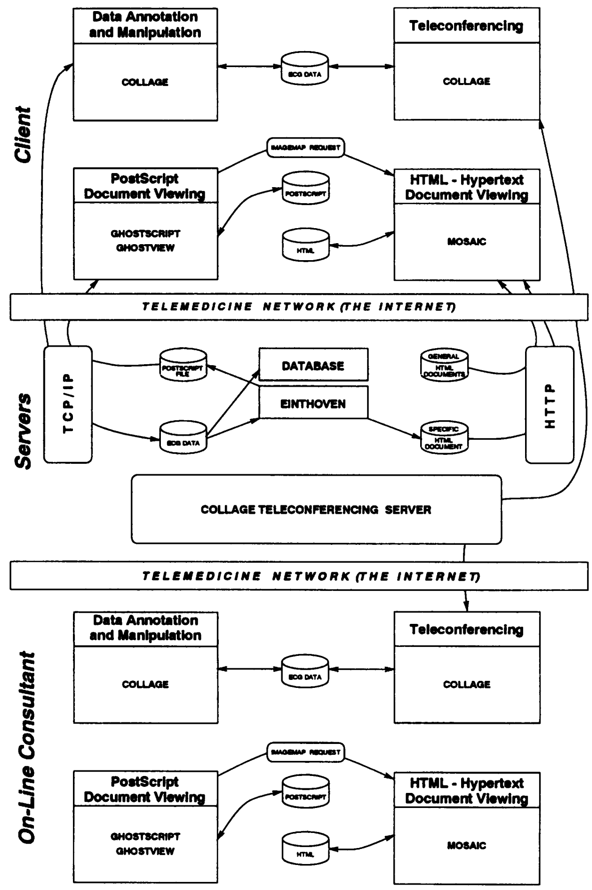

Figure 1: *Schematic Representation of the Telemedicine System*

"Expert" ECG Interpretation

The core of the described system produces a complete set of interpretations, given a complete description of the features of a rhythm strip. This system, named EINTHOVEN after a pioneer in the field of electrocardiography, has been under development since 1990 [6, 7, 8].

The input to EINTHOVEN is a straightforward description of the electrical waves in the rhythm strip. The rhythm strip consists of a sequence of the smaller P waves, which are generated by the atria (upper chambers of the heart), and of the larger QRS complexes and T waves, which are generated by the ventricles (lower chambers of the heart). The description for each wave required by EINTHOVEN consists of the onset time, width, and shape classification for each wave. The shape classification for P waves and T waves reflects whether the shape of a given wave is similar or dissimilar to the shapes of the other P and T waves, respectively. The shape classification for QRS complexes includes a comparison to the other QRS complexes in the recording and a comparison to the shape that is characteristic of a particular abnormal type of QRS complex that arises from the ventricles.

Rhythm analysis is performed by EINTHOVEN using the hypothesis-and-test paradigm in a beat-by-beat manner. Based on the input data, EINTHOVEN constructs patient-specific models from a comprehensive semi-quantitative model of the cardiac conduction system using two production-rule knowledge bases. The patient-specific models are simulated using discrete-event simulation techniques to produce the individual waves that are expected to be seen in the rhythm strip provided the model is a correct description of the patient's state. These expected model behaviors are compared to the observed data, which leads to the creation of new models to explain any discrepancies or to the refinement of existing models to better reflect the patient's state.

The output of EINTHOVEN is a set of ladder diagrams, one for each possible interpretation of the given rhythm. Ladder diagrams provide a concise method of describing the origin and consequences of cardiac depolarizations and is standard in the cardiology literature. In most cases, a single ladder diagram interpretation is adequate to explain fully a given ECG. However, in some cases, multiple ladder diagram interpretations are necessary. EINTHOVEN has been shown to perform competently at the level to be expected of a trained Coronary Care Unit nurse or Intern-level physician [9, 10]. We are continuing to enhance the capabilities of EINTHOVEN [11, 12, 13].

This system is designed not to render an interpretation if it does not recognize the rhythm, and it is also designed to render all possible interpretations that are consistent with a given rhythm. Thus, by design, this novel system is safe and effective.

Data Annotation and Manipulation

For ECG analysis using EINTHOVEN, the user must identify the waves present in the ECG, especially the P waves. Until automated methods for reliably identifying all waves present in the ECG become available, users will be required to annotate the ECG to identify the waves. As a result of this requirement, the system was designed to display scanned ECG images and provide the necessary tools for identifying the waves, such as drawing, moving, copying, and deleting boxes, entry fields for wave type and shape, and image calibration.

To provide this functionality, we modified and enhanced the Collage system developed by the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign [14]. Collage, the Collaborative Analysis and Graphics Environment, is a network-based data analysis tool that allows multiple users to share a common "whiteboard" in a heterogeneous computing environment via the Data Transfer Mechanism (DTM) protocol [15]. Using Collage, multiple users can connect with each other over the network and share data visualization in the form of raster images, palettes, animations, and scientific datasets. Collage contains facilities for electronic whiteboard conferences, image and text display and editing, and screen capture. In addition to Collage's existing functionality, such as buttons for drawing boxes and lines, entering text, and changing colors, we added the necessary ECG annotation functionality, such as wave identification and image calibration.

Output Display

For ECG analysis output, we have implemented a component that is able to view and print PostScript files. The PostScript format was chosen because of its desirable technical advantages: (1) it utilizes the "sheet of paper" paradigm, (2) the defined pages are infinitely scalable on the user's screen, (3) the files can include multiple pages, and (4) the files are device-independent. The first advantage allows for the straightforward generation of the overlay grid for hypermedia linking via the Hypertext Markup Language (HTML) and the Hypertext Transmission Protocol (HTTP) of the image coordinates to hypermedia documents for a distributed context-sensitive help facility. The second advantage is useful because finer details can be displayed in small type. If the user is not interested in them, they are not obtrusive. If they are of interest, they can be displayed at high magnification ("zoomed") by the PostScript viewing component. The third advantage is useful because output from EINTHOVEN may be several pages in length, depending upon the complexity and length of the ECG. The fourth advantage allows the images to be viewed on the screen of most major hardware platforms with a platform-specific viewing program and to be printed by any PostScript printer on the market. To provide this functionality to the system, we included the GhostScript PostScript image viewing libraries [16] and modified and enhanced the Ghostview viewing program [17], both of which are freely available on the Internet under the GNU license.

Hypermedia Display

Since many telemedicine users may be not be specialists in the medical domain for which the telemedicine application was developed (namely cardiology), an explanation facility is included to provide explanations of EINTHOVEN's reasoning and output and to provide access to general hypermedia-based medical literature via the Internet. The hypermedia-based explanation files are generated by EINTHOVEN. With this functionality, users are able to select between case-specific or general levels of detail based on their own needs.

Resources are readily available on the Internet for creating and disseminating hypermedia documents and associated image and sound files. The HTML [18] is a proposed international standard for hypermedia documents on the Internet [19, 20, 21]. HTML specifies a series of descriptors embedded in a text document that specify the manner in which text, images, and sound will be presented to the user. HTML also includes specifications for linking together HTML-formatted documents. Another facility allows an imagemap, an invisible overlay or grid, to be associated with an image to establish hypermedia links from specific image coordinates defined in the imagemap to related information. Using the imagemap facility, mouse clicks in an image with a defined imagemap will lead to the retrieval of the hypertext document associated with the image coordinates at the location of the mouse click. The power of this method lies in the HTML interpreter programs, or browsers, that are freely available on the Internet. For HTML-formatted document display, we have modified and enhanced the Mosaic program [22] developed at the NCSA.

Interactive On-line Consultation

Collage was utilized for the interactive on-line consultation component. In this role, Collage clients connect to a server that conforms to the DTM standard. In this manner, two or more Collage clients can connect to each other through a DTM server to form a distributed teleconferencing session. Collage implements the "whiteboard" conferencing concept in which one participant loads an image into his or her Collage client. The same image is transmitted to all other participants through the DTM server. When one participant draws on the image using the image manipulation features of Collage, all session participants see the drawing action as it occurs. In addition to the whiteboard form of communication, Collage includes a text-based "chat" facility that allows participants to enter text messages that are reflected to all other participants through the DTM server. The features of Collage allow teleconference participants to communicate in real time using either images or text.

Servers

Three network communication servers have been implemented in the system. Two existing software packages (DTM and HTTP) were utilized and a new server was developed to manage the necessary client-server medical data communication, such as the transfer of ECG images and annotations from the client to EINTHOVEN and the transfer of the output PostScript file from EINTHOVEN to the client.

The Data Transfer Mechanism The DTM [15] was designed to simplify interprocess communications and to facilitate the creation of data-intensive distributed applications in a heterogeneous computing environment. A server has been developed at NCSA as part of the Collage package that uses DTM to route messages between clients connected in a whiteboard teleconference in a fan-in, fan-out fashion. All DTM clients connected to a DTM server session send messages to the server. The server then routes these messages to all other clients connected to the same session. This model allows for simultaneous messages to be passed between the DTM server and multiple DTM clients. We have augmented this server by adding security features that will monitor client connections (only allowing registered clients to connect and limiting the number of allowed connections per server). The DTM and the DTM server form the telecommunication basis for the aforementioned teleconferencing module.

The Hypertext Transmission Protocol: The HTTP [23] is a fast, stateless information retrieval TCP/IP-based protocol for serving hypertext documents in a distributed environment. HTTP was developed by the European Laboratory for Particle Physics (CERN) as part of the World Wide Web (WWW) project, a wide-area hypermedia information retrieval initiative aiming to give universal access to a large universe of documents. We have implemented the HTTP server developed by CERN. Although not yet implemented as part of the described telemedicine system, the security and user authentication capabilities of the HTTP server will be utilized in the future.

The Telemedicine Data Server: We have developed a client-server interface for transmitting medical data between the client program and the server that runs EINTHOVEN. This server accepts the scanned ECG image file and user annotations from the client, executes EINTHOVEN on the annotation data file, and returns the PostScript file generated by EINTHOVEN and the location of the associated hypertext explanation documents to the client. This server was written using the TCP/IP protocols.

Evaluation

To examine the system's performance on the desired delivery computer hardware platforms, two preliminary evaluations were performed. The first evaluation examined the network response of the system while running the client on a Sun Microsystems Sparc 2 in New Orleans, LA. The second evaluation consisted of running the client portion of the system on (1) an Apple Macintosh Quadra with 8 MB of memory and System 7.0 running MacX Version 1.2 (Apple Computer, Cupertino, CA) and on (2) an Intel 486/33-based computer with 16 MB of memory, MS-DOS Version 6.22, Microsoft Windows Version 3.1, and PC/TCP Version 2.3 (FTP Software, North Andover, MA) running two X servers, DesqView X, Version 2.0 (Quarterdeck Office Systems, Santa Monica, CA) and X/Vision 5, Version 5.0 (VisionWare, Menlo Park, CA). In all evaluations, the servers ran on a Sun Microsystems Sparc 1+ with 16 MB of memory in Oklahoma City, OK.

RESULTS

The described system was successfully developed on Sun Microsystems Sparc-based computers (Sparc 2's and 1+'s) running SunOS 4.1.1 using gcc version 2.6.3 [24]. The developed system is statically linked to the various libraries and occupies 6.1 MB of disk space. Approximately 2.5 man-months were required to develop the system.

In the first evaluation when running on the Sparc 2, the system required just over five seconds to load. Data transmission over the network was quite acceptable, even when using the system during the peak network traffic hours of the Internet.

Running the system on the personal computers with X server software was not acceptable. MacX and DesqView X were not able to run the system. The MacX server was not able to run the system and displayed an uninformative error message. The DesqView X server failed to run the system with no displayed error messages. The X/Vision 5 X server was able to at least run the program, but the average startup time was over three minutes. Attempting to open the data annotation component of the system caused a server error, thus terminating the execution of the system. X/Vision 5 did not produce any error messages when this occurred.

To investigate whether or not these findings were a result of our software design methodology (i.e. merging distinct software resources to produce a single program), we attempted to run the X version of the Mosaic browser, a component resource used in our system, on the individual systems. MacX was not able to run Mosaic. Desqview X and X/Vision were able to run Mosaic, but each had its own limitations. Desqview X would load Mosaic in a timely manner (under 30 seconds), but the user lost control of the mouse. X/Vision required over four minutes to load Mosaic. Once running, the response time of Mosaic using this server was prohibitively slow.

DISCUSSION and CONCLUSIONS

Rapid development of complex client/server-based system using readily-accessible resources on the Internet is possible. No significant obstacles were encountered when adapting the existing resources for use with the telemedicine system.

Current personal computer X servers do not execute complex X-based clients with sufficient speed and reliability to be used as a delivery modality for personal computers. This limitation was not due to the design of our system, but appears to be due to the limited ability of available X servers to use the processing power of the targeted personal computer platforms. Due to this limitation, developing cross-platform applications requires the use of specially designed cross-platform development tools that will enable complex systems to run natively on personal computer hardware platforms. We are reimplementing the telemedicine system using the Galaxy Release 2.5 (Visix, Reston, VA) cross-platform development environment.

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